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In Line Optical Fibre Frequency Shifter Project - Final Report

[Grant reference AFOSR 91-0114 JACKSON]

Dr. M. Berwick and Prof. D. A. Jackson

Applied Optics Group,

The Physics Laboratory, University of Kent,

CANTERBURY, Kent. CT2 7NR. U.K.

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Dr. M.BERWICK and PROF. D.A. JACKSON

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Department of Physics,
CANTERBURY,
Kent. CT2 7NR.

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13. ABSTRACT (Maximum 200 words)

This report summarises the results of the research programme on the development of a torsional acoustic wave coupled birefringent optical fibre frequency shifter. It describes the results of research directed towards improving the performance of the torsional-birefringent optical fibre frequency shifter introduced near the completion of the previous contract: AFOSR Contract F49620-88-C-0123.

A detailed account is given of the experimental procedures required to construct and test a fibre-optic frequency shifter utilising a travelling torsional acoustic wave to couple the polarisation eigenmodes of a highly linearly birefringent optical fibre. The frequency shifter configuration is such that the acoustic wave generator and optical fibre are co-axial. The device is thus more rugged than previous 'free fibre' frequency shifters where the acoustic wave is coupled into the fibre via an acoustic horn bonded to the edge of the optical fibre.

Results are presented for the best device constructed thus far. The optical frequency shift was 3.204 MHz and an optical coupling efficiency of 12% was obtained with 4W of electrical power applied to the acoustic transducer. Carrier and sideband suppressions of 25 and 30 dB were attained.

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This technical report has been reviewed and is approved for publication.

PARRIS C. NEAL, Lt Col, USAF
Chief, Applied Electronics

RONALD J. LISOWSKI, Lt Col, USAF
Chief Scientist

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Dr. M. Berwick and Prof. D. A. Jackson

Applied Optics Group,

The Physics Laboratory, University of Kent,

CANTERBURY, Kent. CT2 7NR. U.K.

Contents

Summary

This report summarises the results of the research programme carried out by the Applied Optics Group at the University of Kent at Canterbury, U.K., on the development of a torsional acoustic wave coupled birefringent optical fibre frequency shifter. This work was funded by the United States Air Force Office of Scientific Research under grant reference AFOSR 91-0114, for the period 1st January 1991 to 31st December 1991. The principal investigator for this project was Prof. D. A. Jackson and the research associate was Dr. M. Berwick.

This report describes the results of research directed towards improving the performance of the torsional-birefringent optical fibre frequency shifter introduced near the completion of the previous contract: AFOSR Contract F49620-88-C-0123 (1st Jan '89 - 31st Dec '90).

A detailed account is given of the experimental procedures required to construct and test a fibre-optic frequency shifter utilising a travelling torsional acoustic wave to couple the polarisation eigenmodes of a highly linearly birefringent optical fibre. The frequency shifter configuration is such that the acoustic wave generator and optical fibre are co-axial. The device is thus more rugged than previous 'free fibre' frequency shifters where the acoustic wave is coupled into the fibre via an acoustic horn bonded to the edge of the optical fibre.

Results are presented for the best device constructed thus far. The optical frequency shift was 3.204 MHz and an optical coupling efficiency of 12% was obtained with 4W of electrical power applied to the acoustic transducer. Carrier and sideband suppressions of 25 and 30 dB were attained. The coupling efficiency, carrier and sideband suppressions achieved for this device, while significantly improved on previous similar devices, are significantly lower than theoretical prediction and this is attributed to the difficulties in manufacturing the unit.

Finally, proposals for future work are outlined which should lead to further improvements in the efficiency and ruggedness.

1. Theory and Development of the Torsional-Birefringent Fibre Frequency Shifter

Introduction

Many optical fibre sensor systems utilise signal processing schemes based on the production of a continuous heterodyne carrier[2]. True heterodyne processing necessitates the use of a multiple frequency optical source or an optical frequency shifter. The acousto-optic Bragg cell has been conventionally used to shift optical frequencies. However, as this is a bulk-optic component it is incompatible with all-optical-fibre systems. An optical frequency shifter in fibre form is thus a highly desirable component and the development of such devices has attracted a large number of workers in recent years[3-9].

An optical fibre frequency shifter has two main elements. These are firstly, an optical fibre which in its unperturbed state supports two initially orthogonal optical modes and secondly, a means of inducing a travelling perturbation in such a way that, in the perturbed state, optical power can be efficiently exchanged between the modes.

The optical fibre frequency shifter presented in this report was developed from the device reported in references 1 and 9. Both devices are based on acousto-optic coupling of the two orthogonal polarisation eigenmodes of a highly linearly birefringent fibre. A device using this fibre will be easier to incorporate into existing sensor systems than one based on two-spatial moded fibre, as used by some workers[5]. The travelling perturbation is a torsional acoustic wave, excited on the free fibre. In some devices a surface acoustic wave generator is used[3] and the fibre is held in close contact with the substrate to maximise the efficiency of the acoustic coupling. These devices are potentially more rugged, however 'free fibre' configurations are more efficient as they exploit the greater concentration of acoustic energy in the vicinity of the fibre core. Torsional acoustic waves are used as this acoustic mode has been shown to be more efficient than the flexural mode at effecting the polarisation mode coupling[9].

Previous optical fibre frequency shifters with free-fibre constructions, whether employing flexural[3] or torsional[9] acoustic waves, have incorporated a fused T-junction joint between the unjacketed optical fibre and the acoustic wave generator (fibre-to-silica acoustic horn and fibre-to-secondary fibre respectively). These joints lead to shear stresses across the optical fibre and are inherent weak points in these structures. The practical application of these devices is thus limited. The fibre frequency shifter reported here is more rugged because the optical fibre and acoustic wave generator are co-axial.

Theory

A brief outline of the theory of operation of acousto-optic frequency shifters is given in this section; for a more detailed discussion refer to reference 1.

Coupled mode theory[11] can be used to analyse the transfer of power between two (or more) optical modes by a travelling acoustic perturbation. The two modes, here the polarisation eigenmodes of a linearly birefringent optical fibre, have associated amplitudes $A_1(z)$ and $A_2(z)$. Then given the initial conditions $A_1(0) = 1$ and $A_2(0) = 0$, that is only one eigenmode is populated at the start of the interaction region, the fraction of power coupled from mode 1 to mode 2 in an interaction length z is given by,

$$P(z) = \left|\frac{A_2(z)}{A_1(0)}\right|^2 = \frac{|\kappa|^2}{|\kappa|^2 + \left(\frac{\Delta\beta}{2}\right)^2} \sin^2\left(z\sqrt{|\kappa|^2 + \left(\frac{\Delta\beta}{2}\right)^2}\right) \qquad (1a)$$

$$\Delta\beta \equiv \beta_1 - \beta_2 - K \qquad (1b)$$

κ is the coupling coefficient for a perturbation, here a fundamental torsional acoustic mode, copropagating with the light. β_1 and β_2 are the propagation constants of the two optical modes and K is the angular wavenumber of the perturbation. From equation (1b), complete power transfer ($P(z) \equiv 1$) can only occur if $\Delta\beta \equiv 0$. This is known as the longitudinal phase matching condition and is equivalent to matching the spatial period of the perturbation, Λ, to the beat length between the two modes, L_B. The travelling perturbation gives rise to a frequency shift in the coupled light given by,

$$\Delta\omega = \omega_2 - \omega_1 = \frac{\beta_2 - \beta_1}{|\beta_2 - \beta_1|}\Omega \qquad (2)$$

where ω_2 and ω_1 are the optical frequencies associated with modes 1 and 2 of the fibre respectively and Ω is the angular frequency of the perturbation. For a counterpropagating acoustic wave the frequency shift is of equal magnitude but opposite sign. Following the method of Pannell[6,10], the coupling coefficient may be derived,

$$\kappa = \frac{2\pi\,\Theta}{L_B} \tag{3}$$

Hence the angular displacement, Θ, required for complete coupling by a torsional perturbation is given by,

$$\Theta(100\%) \approx \left(\frac{L_B}{4\,z}\right) \tag{4}$$

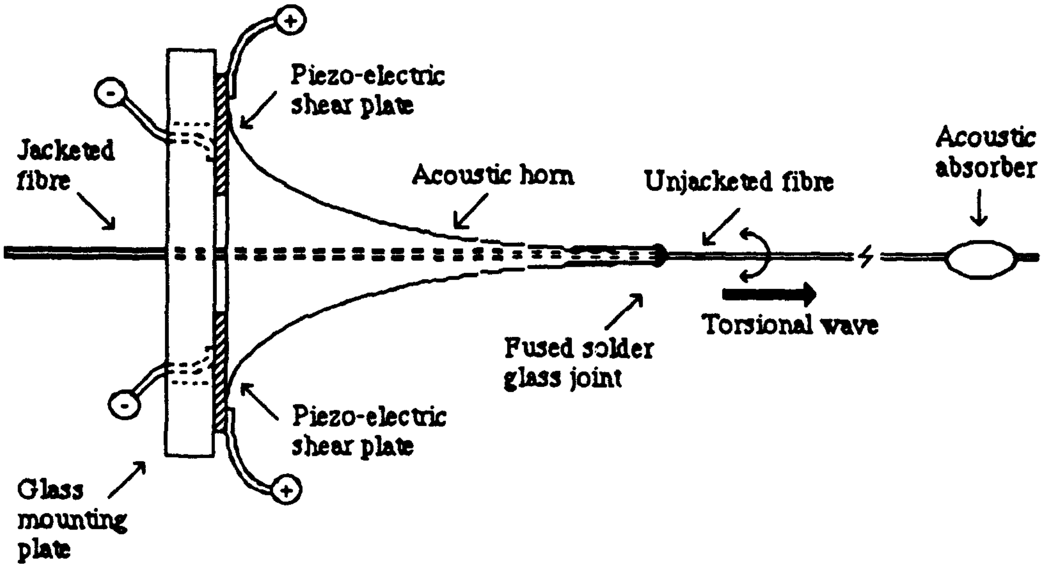
For example, if $L_B = 1.2$ mm and $z = 50$ cm then $\Theta(100\%) = 0.6$ mrad. Given a fibre diameter of 125 μm, this corresponds to a peak fibre surface displacement of 37.5 nm.

Development of the torsional-birefringent shifter design

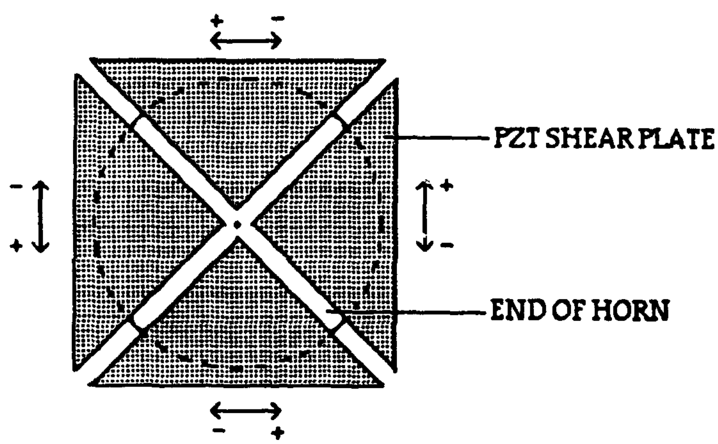
The torsional-birefringent fibre frequency shifter reported in reference 1 had an optical coupling efficiency of only ~2.5%. Coupled mode theory shows that with a sufficiently large acoustic wave amplitude for the given interaction length and perfect longitudinal phase matching, 100% coupling efficiency is achievable.

A schematic of the previous prototype is shown in figure 1.1. Two main areas in the construction of the original prototype were identified for improvement in order to increase the coupling efficiency:

(1) The design of the torsional transducer is not optimal for the efficient generation of a torsional acoustic mode as the triangular shaped piezoelectric elements cover almost the whole of the end of the acoustic horn. Thus the shear displacement that the elements couple into the horn in order to excite the acoustic wave is approximately constant over the whole circular cross-section, as the shear amplitude depends only on applied voltage and electrode separation, not on electrode area. A constant shear amplitude is not matched with the fundamental torsional acoustic mode whose amplitude increases proportionally with radius from the centre of a circular cross-section body. Hence, an improvement in the torsional transducer design to match the piezoelectrically induced shear amplitude distribution to the torsional mode would lead to a direct increase in the acoustic amplitude and concommittant increase in the coupling efficiency.



(A)



(B)

<u>Figure 1.1 : Schematic of (A) Prototype torsional-birefringent fibre frequency shifter (B) Torsion generator configuration</u>

(2) The diameter of the tip of the horn must be reduced such that it is closer to the outer diameter of the optical fibre which passes through it. The effect of this would be to improve the acoustic impedance matching at the horn tip-optical fibre joint with concommittant increase in the torsional acoustic amplitude in the interaction region, further increasing the coupling efficiency.

No improvements on previous results were obtained when further torsional wave generators were constructed using either four or six triangular shaped pzt transducers, cut from plates supplied by the manufacturer. The resonance frequency of these plates was not exactly matched to the acoustic frequency required to satisfy the longitudinal phase matching condition, hence enhanced performance would be achieved by controlling the plate thickness and hence resonance frequency. The shape and positioning of the PZT elements are not optimal and thus it was decided that the most likely alternatives would be investigated experimentally while a theoretical analysis was carried out under another contract; the results of which were not available during this contract, despite this a different transducer configuration was tested and proved more successful; it is reported in sections 2 and 3. The premise behind the new design was that the PZT transducer only generated useful torsional acoustic power when attached to the outer part of the acoustic horn. This hypothesis was tested using the simplest shape PZT transducers to produce, i.e. square transducers, attached to the outer half of the acoustic horn diameter. This design of torsional transducer is discussed in greater detail in sections 2 and 3.

The horn tip diameter was successfully reduced by etching with acid the drawn Pyrex horns This is discussed in section 2.4. The concomitant improvement in acoustic impedance matching not only increases the torsional acoustic power transmitted onto the fibre, but also alleviates the potential problem of matching the acoustic horn length to an integral number of acoustic half-wavelengths. With a significant reflection of acoustic power at the tip, the acoustic horn must be considered as a resonant cavity. The torsional amplitude transmitted to the fibre therefore depends on the cavity length. The better the impedance matching at the tip, the smaller the reflection and the less important this effect.

2. Manufacture of a Torsional-Birefringent Fibre Frequency Shifter

Introduction

This section contains a detailed account of the experimental procedures required to construct a practical torsional acoustic wave highly birefringent optical fibre frequency shifter:

2.1 Manufacture of PZT shear plates of approximately correct dimensions

A pzt shear plate is required which is large enough to cut up to form the pzt elements for the torsional transducer and of the correct thickness to give a shear vibration resonance at the required frequency. Given an acoustic horn outer diameter of ~8mm the dimensions of the pzt elements should be 4 mm x 4 mm x $\lambda_{pzt}/2$. To allow for wastage during cutting, the plates were manufactured from a block of shear poled PZT-7A (Vernitron-Morgan Matroc) of dimensions 10 mm x 12 mm x 50 mm. The block is poled through the 12 mm direction, and care must be taken throughout the manufacturing process to identify the poling direction unambiguously. From previous results it is known that the required acoustic resonance frequency is 3.2 MHz, corresponding to a torsional wavelength in fused silica of 1.18 mm, equivalent to the highly birefringent fibre beatlength. From the manufacturers data this resonance frequency corresponds to a plate thickness of:

$\lambda_{pzt}/2$ = shear velocity/(2*resonance frequency) = $2490/(2*3.2*10^6) = 0.39*10^{-3}$ m

A number of 10 mm x 12 mm x ~0.45 mm plates are cut from the block of pzt material using a diamond impregnated disc saw (Logitech Model 15). These plates are then lapped using a precision lapping and polishing machine (Logitech PM2A) to a final thickness in the range 0.39 ± 0.05 mm. Care must be taken during theses stages to minimise mechanical shock to prevent depoling of the pzt.

2.2 Determination of PZT plates resonance characteristics

2.2.1 Electrical measurement

Although the plates were polished on a precision instrument they exhibited a significant spread in characteristics. In order to choose the best plate from which to produce the PZT drive elements for the torsional transducer it was necessary to determine the plate resonance characteristics. The simplest way to do this is to measure the electrical characteristics using a network analyser.

The plates were initially coated on both faces with aluminium by vacuum deposition in order that they could be electrically driven. A network analyser (Hewlett Packard HP4195A) was then used, in the configuration shown in figure 2.1, to measure the electrical characteristics of the plate. The frequency swept source is applied to the plate and the transmission characteristic measured as a function of drive frequency. A typical characteristic measured in this way is shown in figure 2.2. From this type of plot the main resonance frequency of the plate can be identified, and only if this frequency (approximately) matches the frequency required to match the beatlength of the fibre is the plate processed futher as indicated below. This process is extremely time consuming as the yield has been relatively low.

2.2.2 Vibration measurement using the optical vibrometer

The shear vibration amplitude of the selected plates were then measured to ensure that sufficient amplitude could be generated at the desired drive frequency. This also confirmed that depoling of the pzt material had not occured during processing. This measurement is made by first attaching a small reflector (a few mms of tinned wire) to the face of the plate close to one edge. The plate is mounted on an xyz translation stage. This stage is then used to position the reflector at the focus of the heterodyne optical linear vibrometer, shown in figure 2.3. The plate is excited at the resonance frequency identified from its electrical transmission characteristic. Vibration of the plate produces phase modulation of the vibrometer output carrier frequency. The form of this modulation is similar to a classical F.M. spectrum where the modulation index is directly proportional to the vibrational amplitude and may be determined by taking appropriate ratios of the

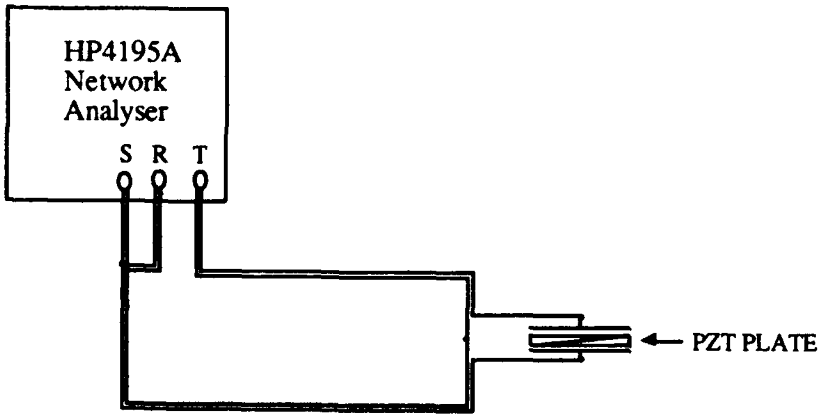


Figure 2.1 : Measurement of the electrical transmission characteristic of a PZT plate

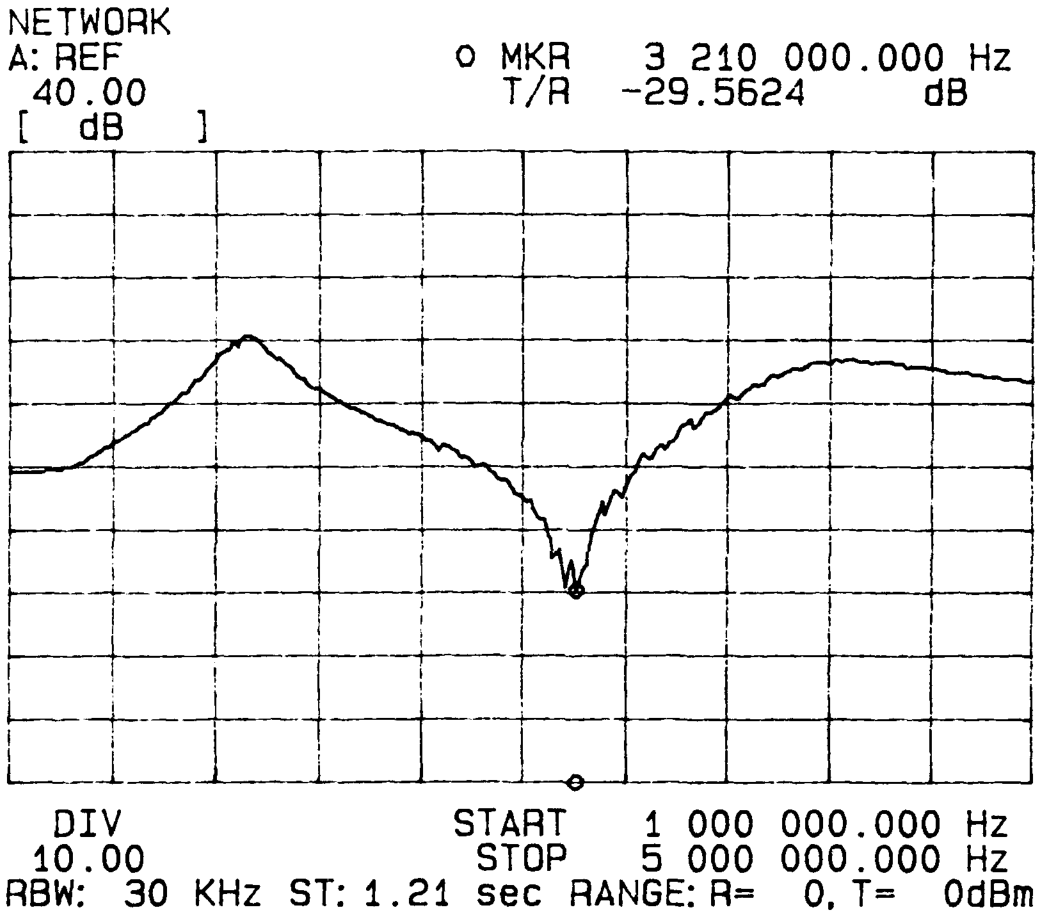


Figure 2.2 : Typical PZT transmission characteristic

Plate thickness = 0.405mm

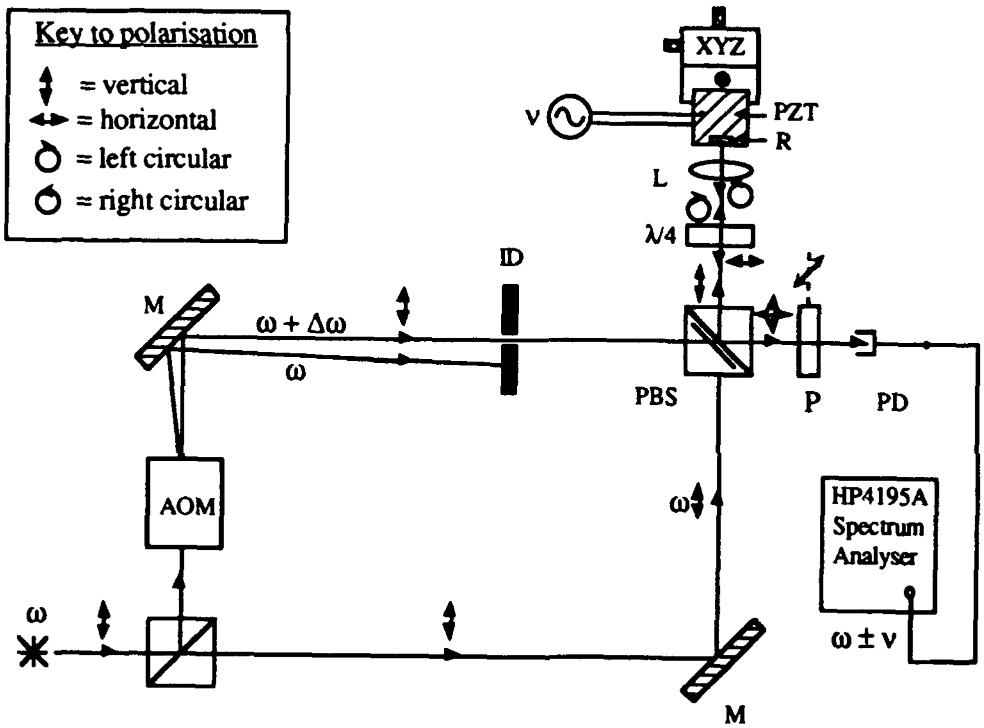


Figure 2.3 : Measurement of vibration amplitude with the optical vibrometer

sideband amplitudes at multiples of the plate drive frequency. Earlier work had shown that unless the vibrational amplitude of a plate was greater than ~20nm, it was not worthwhile using it as the drive unit for the torsional generator (fibre interaction length ~50cm). Vibration amplitudes of this order of magnitude infer that the $J_1(\phi)$, $J_2(\phi)$ and (for amplitudes >40nm) $J_3(\phi)$ components will be visible in the output signal of the vibrometer. The vibration amplitudes were usually very small (of the order of 10nm) and only the first harmonic ($J_1(\phi)$) sidebands were present. By varying the frequency of the applied electrical drive the vibration amplitude for a given electrical power could be optimised. A vibrometer output spectrum is shown in figure 2.4 in which only the $J_1(\phi)$ and $J_2(\phi)$ components are excited, indicating a vibrational amplitude of ~20nm.

2.3 Preparation of the torsional transducer

When a plate capable of producing a usable torsional generator with a resonant frequency within the acceptable range (in this case : 3.2 ± 0.01 MHz) had been identified by the above techniques, it was cut up using a diamond saw to produce the requisite four PZT elements. The elements are then attached to a glass backing plate which forms the mount for the completed device. The configuration of the mount and PZT elements is shown in figure 2.5. The mount is a 20mm x 20mm x ~1.5mm square glass plate with a central hole 10mm in diameter. The PZT elements are attached to the plate with epoxy (Ciba-Geigy Araldite) in a cross-like formation as shown. The acoustic horn is subsequently joined to the front faces of the PZT elements such that PZT material covers only the outer half of the base diameter of the horn. The poling of the elements is sequential around the horn circumference, as shown, so as to generate a torsional acoustic wave in the horn when the elements are excited 'in phase'. As the topology of the pzt drive was not ideal, due to the finite area of the contact points of each driving element, it is feasible that all the energy from the generator may not have been converted to torsional energy. This would result in a lowering of the predicted rotational amplitude of the tip of the horn.

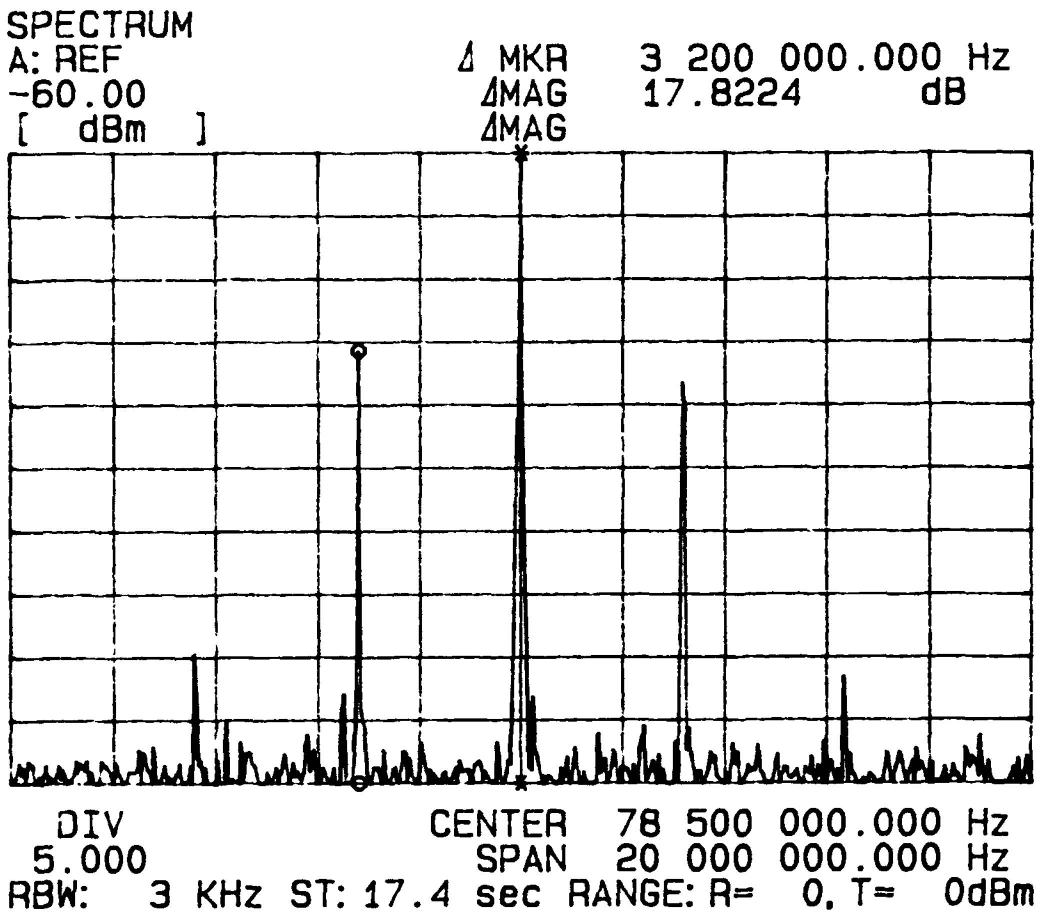


Figure 2.4 : Spectrum obtained from optical vibrometer

Plate thickness = 0.405mm

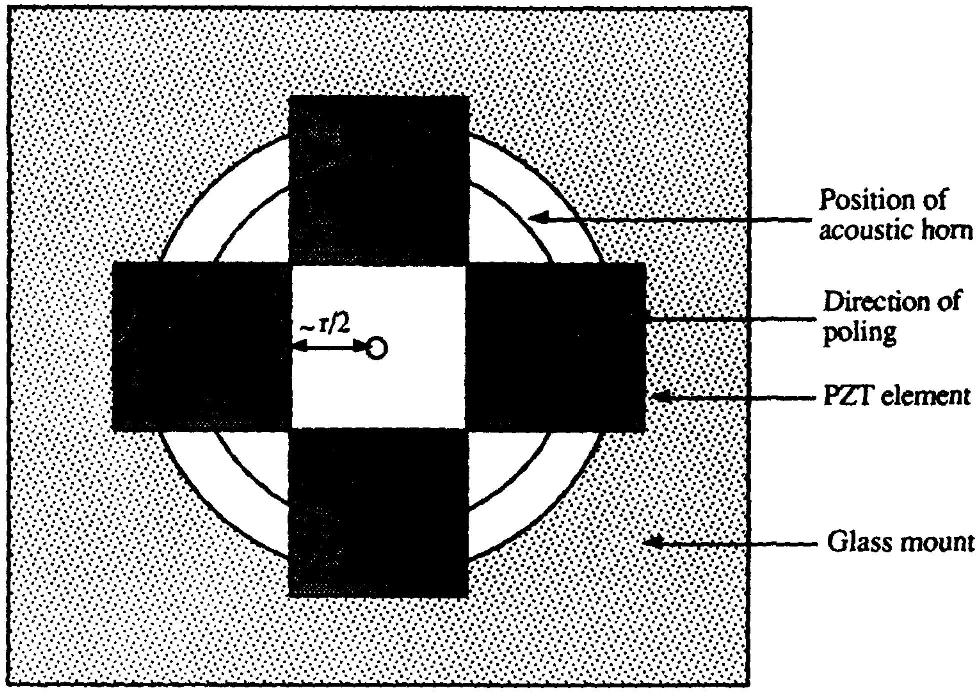


Figure 2.5 : Mounted PZT elements

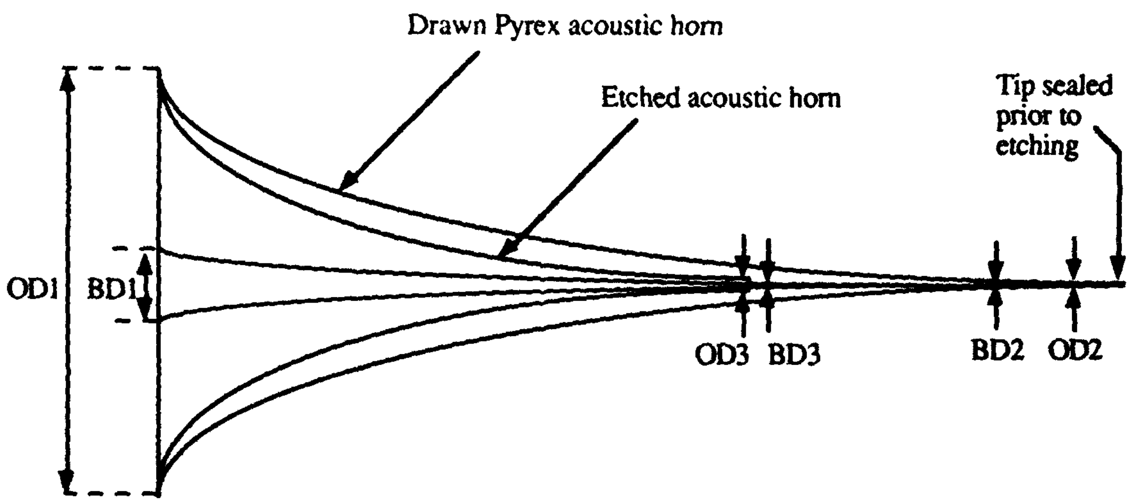


Figure 2.6 : Reduction of acoustic horn tip diameter by acid etching

2.4 Manufacture of the acoustic horn

The acoustic horn is produced by a two stage process. Firstly, a short length of Pyrex capillary tubing, with an outer diameter of ~8mm (OD1 in figure 2.6) and a bore diameter of 1mm (BD1), is carefully drawn down on a glassblower's lathe to give a tapered capillary horn with a concentric tapered bore. As reported in reference 1, the application of a low gas pressure to the bore during pulling permits the bore diameter at the tip (BD2) to be reduced to ~40μm without it closing up; the tip outer diameter (OD2) is then ~350μm. Cleaving back to where the bore diameter is ~130μm (i.e. slightly larger than the optical fibre outer diameter) gives a tip outer diameter of between 0.6 and 1mm. This outer diameter must be reduced to give better acoustic impedance matching between the horn tip and the optical fibre, hence instead of cleaving the drawn fibre tip the outer diameter of the lower half of the horn is reduced by etching with acid. The horn tip is first sealed, using an oxy-propane torch to melt the tip, in order to prevent intrusion of the acid into the bore and any subsequent etching of it. The horn is then suspended partially immersed in 40% hydrofluoric acid while etching occurs.
(N.B. stringent safety precautions must be observed when using this chemical, see chemical safety manuals for the correct procedures!).

Frequent visual checks allow the degree of etching to be monitored, and after thorough neutralisation of the acid residues, BD3 and OD3 can be measured. Careful application of this technique can produce a horn with BD3 ≈ 130μm (to allow the fibre to pass through) and OD3 only slightly larger, such that with a fibre in place it is difficult to detect visually where one ends and the other begins without the aid of magnification! Experimentation has shown that the extremely thin walls in this case are too fragile for subsequent handling (insertion of a length of fibre, etc), and hence it is advantageous to stop the etching process when OD3 ≈ 200μm. This produces a small outer diameter, yet reasonably robust tip.

During initial experiments, the acoustic horn was attached to a motor such that it could be rotated fairly slowly (~6 r.p.m.) in order to provide some stirring of the acid, to prevent any preferential etching of the horn. However, this has been shown to be unnecessary, as circularly symmetric etching occurs equally well without any agitation of the acid.

As discussed in section 1, the length of the acoustic horn should be as close as possible to an integer number of acoustic half-wavelengths. In the work reported here the length of the horn was adjusted by cleaving the etched section with a diamond blade. This is an extremely delicate operation which, if not undertaken with extreme care, can result in the total destruction of the tip of the horn. A possible solution to this problem would have been to polish the base of the horn, though this would also require great care in handling and mounting the horn during polishing.

2.5 Assembly of the torsional acoustic wave generator

The acoustic horn is bonded to the torsional transducer with epoxy to produce the final torsional acoustic wave generator, as shown in figure 2.7. Wire connections must be attached to both aluminised faces of each of the PZT elements in order to connect the electrical drive. The wires are bonded to the PZT electrodes using a two-part, silver-loaded, conducting epoxy. The complete unit is then mounted on a base plate prior to the insertion and jointing of the optical fibre.

2.6 Preparation of the optical fibre

The optical fibre used in the fibre frequency shifter must be of sufficient length to provide the interaction region and both input and output leads. The input lead length should be >0.5 m so that adequate cladding mode stripping may occur. The plastic buffer jacket provides this function, as well as providing mechanical strength and hermetically sealing the fibre surface from the atmosphere. The buffer jacket must be removed from the length of fibre forming the interaction region of the fibre shifter, as it is an efficient acoustic absorber. The interaction length is currently ~0.5 m. The output lead need only be of sufficient length for guiding the shifted output light to the next optical element. Conventional optics were used in the prototype described here, a fibre polariser or polarisation selective fibre coupler would be used in an all-fibre version.

In the current design both the output and frequency shifting parts of the fibre must be stripped of the buffer jacket to allow the fibre to be inserted into the acoustic horn prior to jointing. The buffer jacket can be removed quite simply by immersing the fibre in dichloromethane for a few minutes. This softens the plastic sufficiently for it to be removed cleanly from the fibre with gentle pressure. The stripped fibre must be handled with extreme caution as without the mechanical strength of the plastic buffer it is

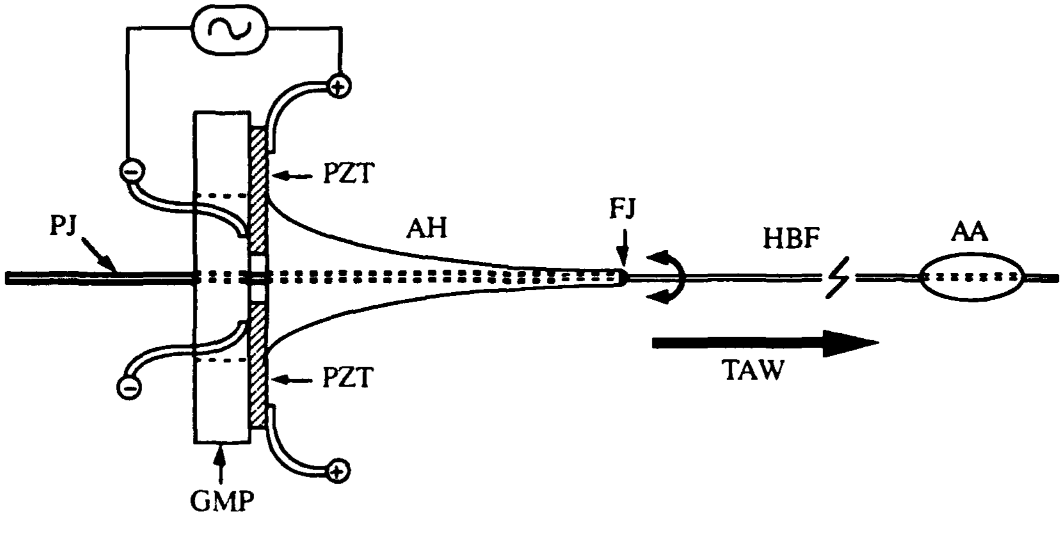


Figure 2.7 : Torsional birefringent optical fibre frequency shifter

[GMP: glass mounting plate, PZT: piezoelectric element, TAW: torsional acoustic wave, AH: acoustic horn, PJ: plastic jacket, HBF: highly birefringent fibre, AA: acoustic absorber, FJ: fused joint] considerably more vulnerable to fracture by shear stresses. After the required amount of jacket has been removed, light should be launched into the fibre for a visual check that the manipulation involved in stripping the jacket has not introduced any fractures. Fracture points increase scattering and are thus visible as glowing points on the fibre. An additional test to establish if internal damage had occurred could be performed with an OTDR system, however such apparatus was not available.

The optical fibre must be cleaned with a solvent (e.g. iso-propyl-alcohol) to remove traces of the dichloromethane and any remaining buffer debris, etc. The optical fibre must then be carefully passed through the bore of the acoustic horn. It is advantageous if the horn is mounted with the core vertical such that the fibre hangs vertically after passing through it. This means that shear forces are not generated in both the horn tip and the fibre itself from the weight of the fibre. Such shear forces can lead to damage of the horn tip and/or breakage of the fragile, stripped fibre. An additional precaution while passing the fibre through the horn, is to arrange for the fibre to pass through a dust-stripper. Despite the chemical cleaning, dust particles inevitably become attached to the fibre surface during handling and must be removed otherwise the tapered bore of the acoustic horn acts as an efficient dust-stripper leading to a build-up of debris at the tip and causing problems during jointing. A simple and effective dust-stripper can be made by passing the fibre between two lint-free cloths dampened with solvent. The fibre is passed through the bore until the buffer jacket, which is not removed from the input lead section of the fibre, just lodges in the bore slightly back from the tip where jointing between the horn and fibre will be carried out.

2.7 Fusing the acoustic horn-optical fibre joint

The optimum condition for achieving a truly concentric joint is with the fibre hanging vertically and freely through the acoustic horn. At present, jointing is achieved by applying a sparing amount of silica jointing paste (American Vitta Corporation type P-1015) to the joint and then fusing this with an oxy-propane torch to bond the two 'glass' surfaces together. The paste should be made just liquid enough such that surface tension produces a symmetric distribution around the joint. The heat from the torch tends to cause the bore of the horn to collapse about the fibre and hence care must be taken not to form a joint with a large degree of in-built shear stress. Even though this stress should be radially symmetric, it may be a factor in subsequent joint failure and cause unwanted static coupling of unshifted light into the output eigenaxis. Using the clamping action of the collapsed bore as the sole jointing mechanism is not desirable for the aforementioned reason. It is preferable to use the jointing paste because when it flows to form the joint, the result is a continuous structure between the horn tip and fibre outer diameters and hence should improve the acoustic impedance matching. An alternative method of jointing could be to use electrical arc fusion, however time did not allow us to fully evaluate this technique. The fusion technique has the potential advantage that the joint can be fabricated without additional material such that perfect acoustic matching might be achievable.

2.8 Completing the fibre frequency shifter

Once the tip-fibre joint is fused and has been allowed to cool, the horn-fibre assembly may be moved to a horizontal position for ease of use (a vertically mounted fibre would reduce the possibility of fibre breakage at the tip but is not practical with the current evaluation configuration due to the need to incorporate the shifter in the test interferometer).

The next operation is to support the stripped fibre at the distal end of the interaction length by setting it in silica rubber compound. The silica rubber not only supports the fibre, providing some stress relief, but also acts as an acoustic absorber thereby defining the end of the interaction region. Figure 2.7 shows the complete fibre frequency shifter configuration.

Light should again be launched in to the fibre to check that it has not been damaged during jointing. One should look for light leaking through the side of fibre at points of actual damage or high stress and check the polarisation holding properties to ensure that the birefringence characteristics have not been radically affected by the heating.

2.9 Evaluation of the fibre frequency shifter

After steps 2.1-8 the shifter is complete and ready for testing . To properly evaluate the shifter it is necessary to incorporate it as one arm of a bulk Mach-Zehnder interferometer, with a Bragg cell in the other arm to generate a heterodyne carrier. This configuration is shown in figure 2.8. The signal from the interferometer output was observed using a spectrum analyser. When the polarisation components of the interferometer are aligned such that the coupled light from the shifter interferes with the light shifted by the Bragg cell, three components are generally present in the spectrum. If the Bragg cell frequency is ω_B and the fibre frequency shifter is driven at ν, then the desired component will be at a frequency of $(\omega_B + \nu)$ (assuming coupling from fast to slow axis). This component is optimised by adjusting ν. The other two components will appear at frequencies of ω_B and $(\omega_B - \nu)$. The component ω_B at the carrier frequency is due to static coupling of the polarisation eigenmodes and $(\omega_B - \nu)$, the downshifted component, is due to incorrect launch conditions (polarisation state and azimuth) and any acoustic wave propagating backwards along the fibre. The suppression of these two spurious frequency components, along with the optical coupled power efficiency, characterise the performance of the fibre frequency shifter.

Once the shifter drive frequency is optimised and the output polarisation selective element, in this case a Glan Thomson polariser, has been adjusted to maximise the shifted component and minimise the spurious components, then the optical coupling efficiency can be simply measured using an optical power meter. The efficiency is then the ratio of the measured power transmitted by the Glan Thomson with the shifter drive on (i.e. shifted component at $(\omega_B - \nu)$) and the measured total power exiting the fibre (i.e. shifted component at ω_B).

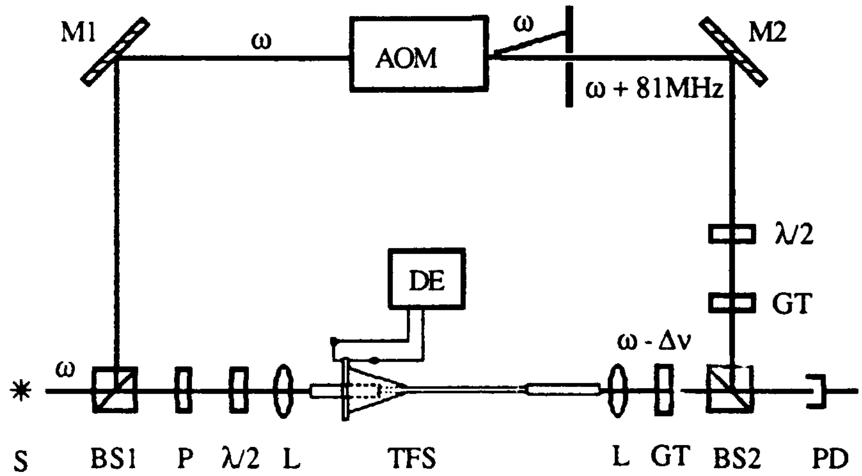


Figure 2.8 : Shifter evaluation configuration

[S:optical source, BS1,2: beamsplitters, P: polariser, λ/2: half-waveplate, L: lens, TFS: torsional fibre shifter, GT: Glan Thomson, PD: photodetector, DE: drive electronics, AOM: acousto-optic modulator (Bragg cell), M1,2: mirrors]

3. Performance of the Torsional-Birefringent Fibre Frequency Shifter

Introduction.

A fibre-optic frequency shifter utilising a travelling torsional acoustic wave to couple the polarisation eigenmodes of a highly linearly birefringent optical fibre, constructed using the method described in section 2, is demonstrated in this section. The device reported exhibited the best performance of all the torsional-birefringent shifters constructed during the research period covered by this report and also those reported in reference 1. The optimum drive frequency, and hence the optical frequency shift, was 3.204 MHz, an optical coupling efficiency of 12% was obtained with 4W of electrical power applied to the acoustic transducer.

Experimental

The configuration utilised to generate torsional waves on the optical fibre is that shown schematically in figure 2.7. The major component is a Pyrex acoustic horn with an axial capillary bore through which the highly linearly birefringent fibre has been passed and joined to the horn tip. The torsional acoustic wave is generated by the combination of four square piezo-electric shear elements attached to the end of the acoustic horn with epoxy adhesive. The four transducers were arranged in a 'cross' pattern with poling directions as shown in figure 2.5, and were each electrically excited in phase.

These elements were produced from a plate selected as described in sections 2.2 and 2.3. A plate selected for its maximum measured vibrational amplitude at 3.195 MHz had a thickness of 0.405 mm. The spectrum of figure 2.2 is the transmission characteristic measured for this plate. Figure 2.4 shows the optical vibrometer spectrum obtained at a drive frequency of 3.195 MHz. From this it can be deduced that the vibration amplitude is approximately 25 nm. Figure 3.1 shows the variation of maximum vibration amplitude, as indicated by the $J_1(\phi)$ component amplitude in the vibrometer output, when the drive frequency was scanned from 1 to 4.5 MHz.

The acoustic horn was manufactured by drawing down Pyrex capillary tubing on a glassblower's lathe and then acid etching the narrower half to further reduce the tip diameter. The base of the horn typically has an outer diameter of ~8 mm and this tapers to an etched tip diameter of ~300 μm, over a length of ~38.5 mm. The bore at the tip is ~130μm. Before insertion of the fibre, a small reflector was attached to the side of the horn tip and the linear

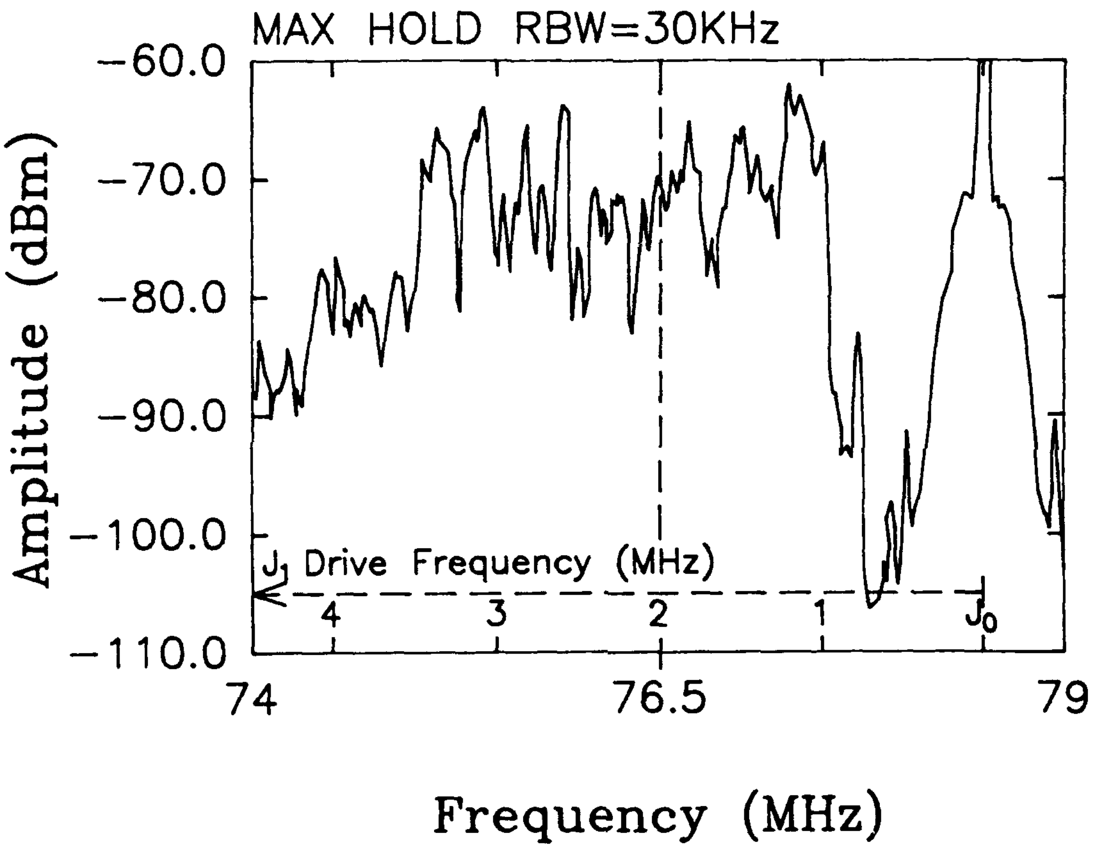


Figure 3.1 : Variation of vibration amplitude as drive frequency is scanned from 1-4.5MHz

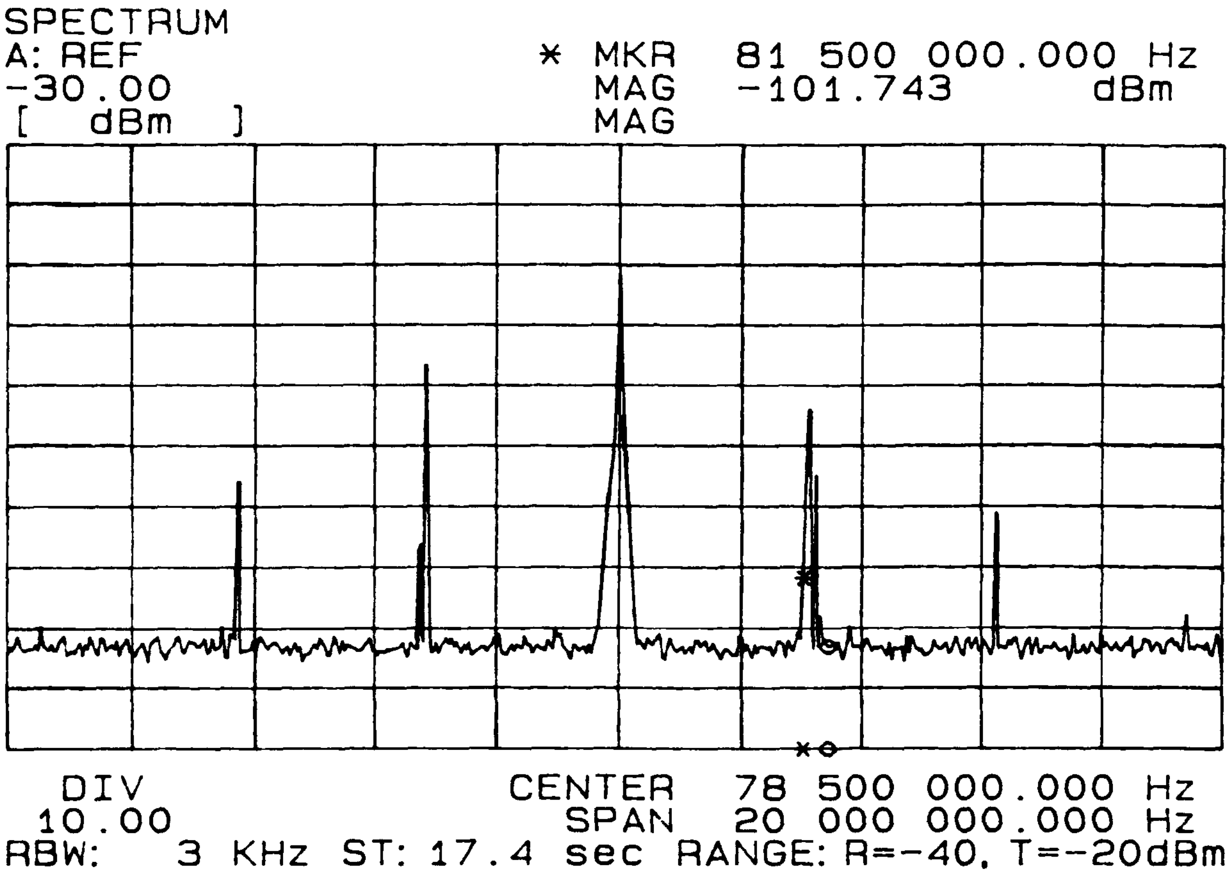


Figure 3.2 : Vibrometer spectrum : measurement made at acoustic horn tip

vibrometer was again used to measure vibration amplitude as a function of drive frequency. The maximum vibration amplitude was achieved at a drive frequency of 3.14 MHz, see spectrum 3.2. The amplitude measured at the tip was ~40 nm; this is effectively the torsional acoustic wave amplitude of the PZT/acoustic horn torsion generator without any loss or loading caused by attaching the optical fibre, but subject to the resonant behaviour of the horn as without the fibre there is a large acoustic impedance mismatch at the tip/air interface.

The fibre used was York Technology 'bow-tie' highly linearly birefringent monomode optical fibre of outer diameter 125 microns. The beatlength of this fibre had been measured by launching linearly polarised light at 45° to its eigenaxes and observing the polarisation dependent Rayleigh scattered light emerging from the side of the fibre. The spatial period of the beat pattern thus observed (equal to the fibre beatlength), was measured with a travelling microscope, and found to be $L_B = 1.2 \pm 0.05$ mm (optical wavelength = 632.8nm). The acoustic frequency required to satisfy phase matching is calculated from the torsional wave velocity for silica, $c_{tors} = 3.77$ kms^{-1} and the torsional acoustic wavelength, λ_{tors}, equivalent to the fibre beat length, L_B. $\nu_{tors} = c_{tors} / \lambda_{tors}$ hence the corresponding torsional frequency is $\nu_{tors} = 3.14 \pm 0.13$ MHz (from previous shifter results $L_B = 1.18$ mm and $\nu_{tors} = 3.2$ MHz).

Silicon rubber compound was applied to the fibre, to act as an acoustic wave absorber, defining an interaction length of ~43 cm of stripped fibre. The gradually reducing bore of the horn allowed the fibre jacket to be left intact inside the horn to within a few millimetres of the join. The fibre jacket gives good suppression of any torsional wave propagating back from the horn tip.

To evaluate its performance this optical fibre frequency shifter was incorporated as one arm of a heterodyne Mach-Zehnder interferometer, see figure 2.8. The piezo-electric plates were excited at a frequency, ν. The reference arm included an 81 MHz Bragg cell acousto-optic modulator. The optical source was a helium-neon laser operating at a wavelength of 632.8 nm. The performance of the fibre frequency shifter was assessed by illuminating a single polarisation eigenmode (slow axis, say) and aligning the interferometer such that the light coupled into the other polarisation eigenmode (fast axis) by the action of the torsional wave, interfered with the light from the reference arm. The light exiting the fibre passed through a Glan-Thomson polariser, oriented to transmit only the light coupled to this (fast) eigenmode.

The frequency spectrum of the output from the detector was investigated using a spectrum analyser. This spectrum contains three components. For the ideal case of zero static coupling and 100% dynamic coupling by a mono-directional torsional wave, a single frequency component at a frequency of 81 MHz - $\Delta\nu$ (slow$\rightarrow$fast axis coupling = downshift) would be present in the spectrum. In practice we also observe a component at the Bragg cell carrier frequency due to static coupled, and thus unshifted, light from the fibre device and an undesired (up)shifted sideband due to backward propagating torsional waves and the imperfection of the input light polarisation state and azimuth.

The optimum drive frequency was found to be 3.204 MHz. The maximum optical coupling efficiency achieved was ~12% (with 4W electrical power applied to the transducers), this was measured both with the spectrum analyser and with an optical power meter. Carrier and sideband suppressions of 25 and 30 dB were obtained. The spectra shown in figures 3.3 and 3.4 correspond to down and up-shifting respectively, due to coupling from the slow to the fast polarisation eigenaxis and vice versa. Figure 3.5 shows the shifted sideband amplitude as a function of drive frequency (central peak is at 3.204 MHz). Figure 3.6 is a plot of optical coupling efficiency (P(z)) versus acoustic frequency generated by inserting the relevant data from this shifter into equation 1. The data includes an estimate of the coupling coefficient based on the measurements made for this device, hence the maximum coupling efficiency is ~12% (-9.2dB). As can be seen, figure 3.5 contains features from both the acousto-optic resonance data of figure 3.6 and the piezo-electric resonance data of figure 3.1.

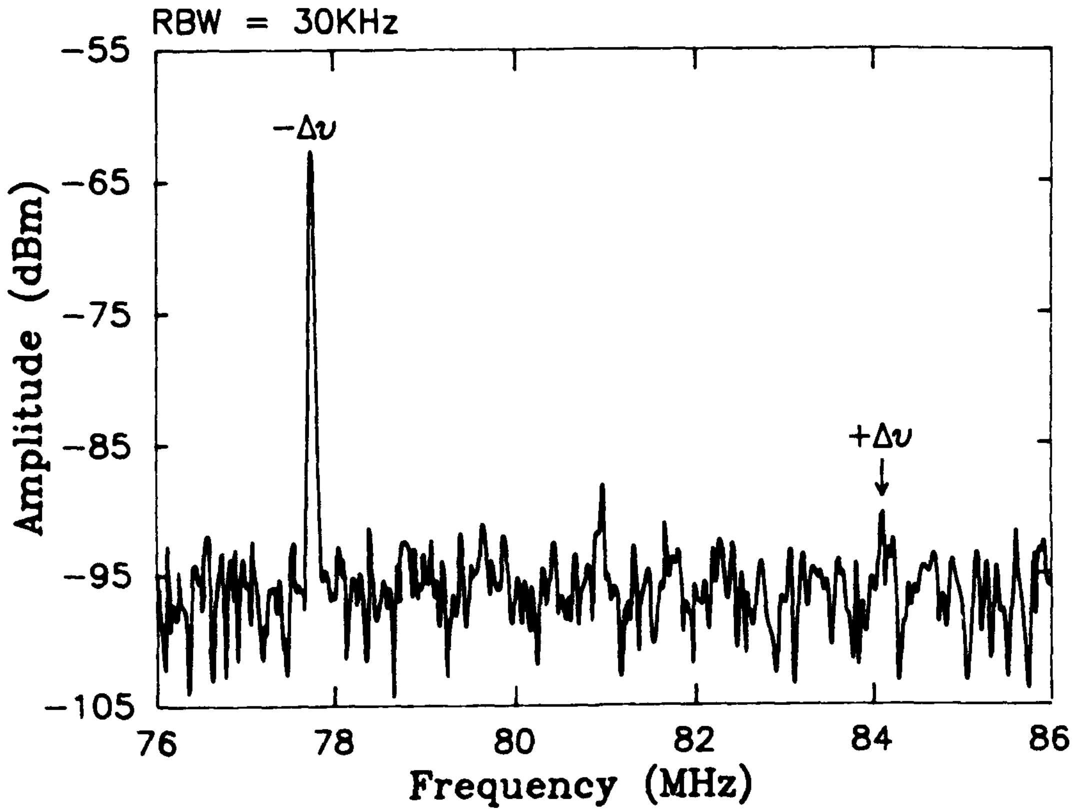


Figure 3.3 : Spectrum corresponding coupling from:
Slow to Fast axis = Downshift. Drive frequency = 3.204MHz

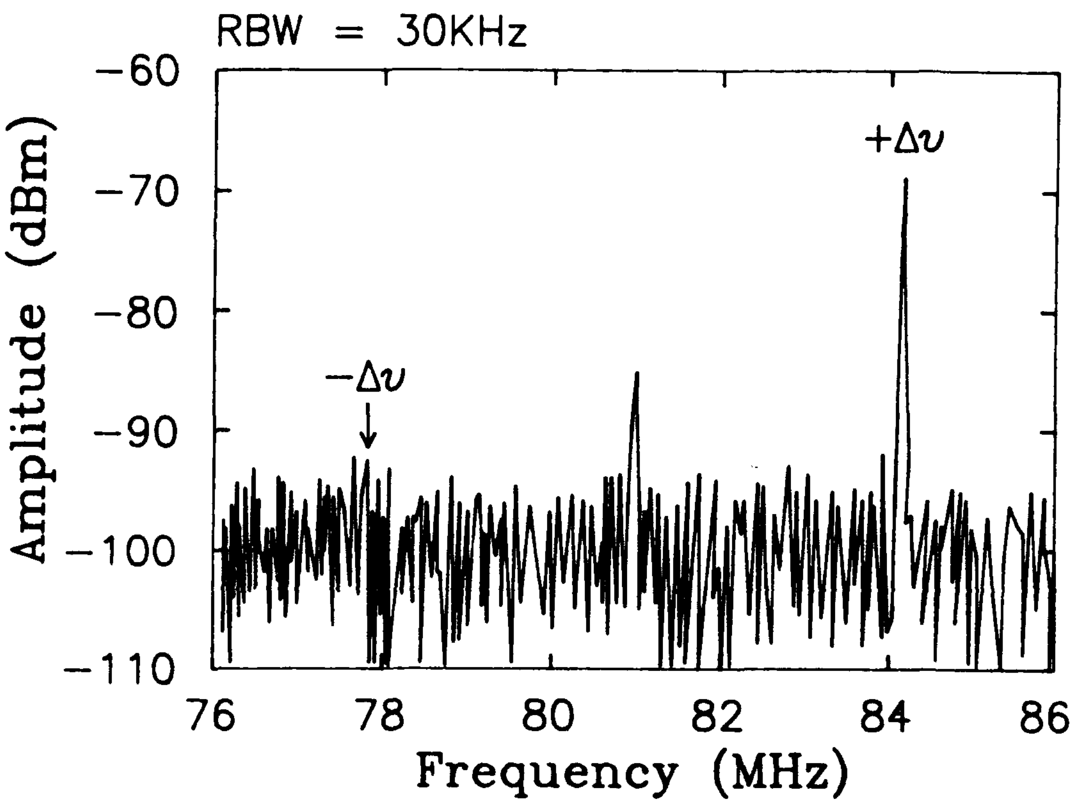


Figure 3.4 : Spectrum corresponding coupling from:
Fast to Slow axis = Upshift. Drive frequency = 3.204MHz

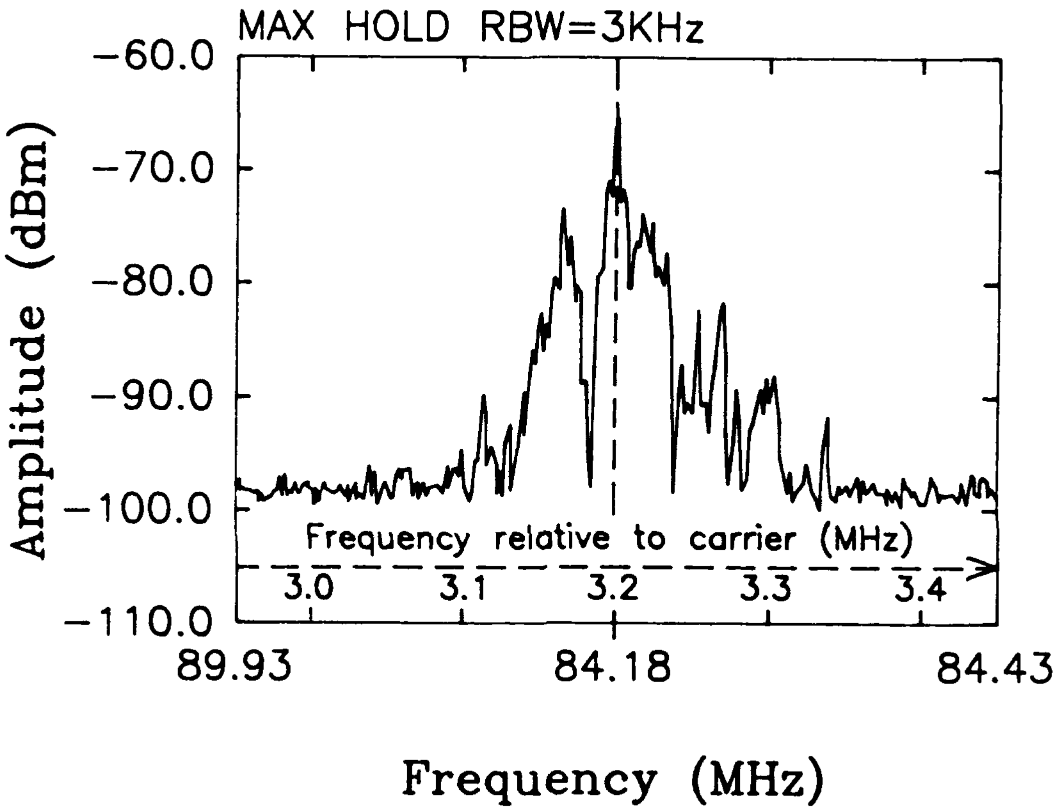


Figure 3.5 : Shifted sideband amplitude as drive frequency is scanned from 2.95 - 3.45 MHz

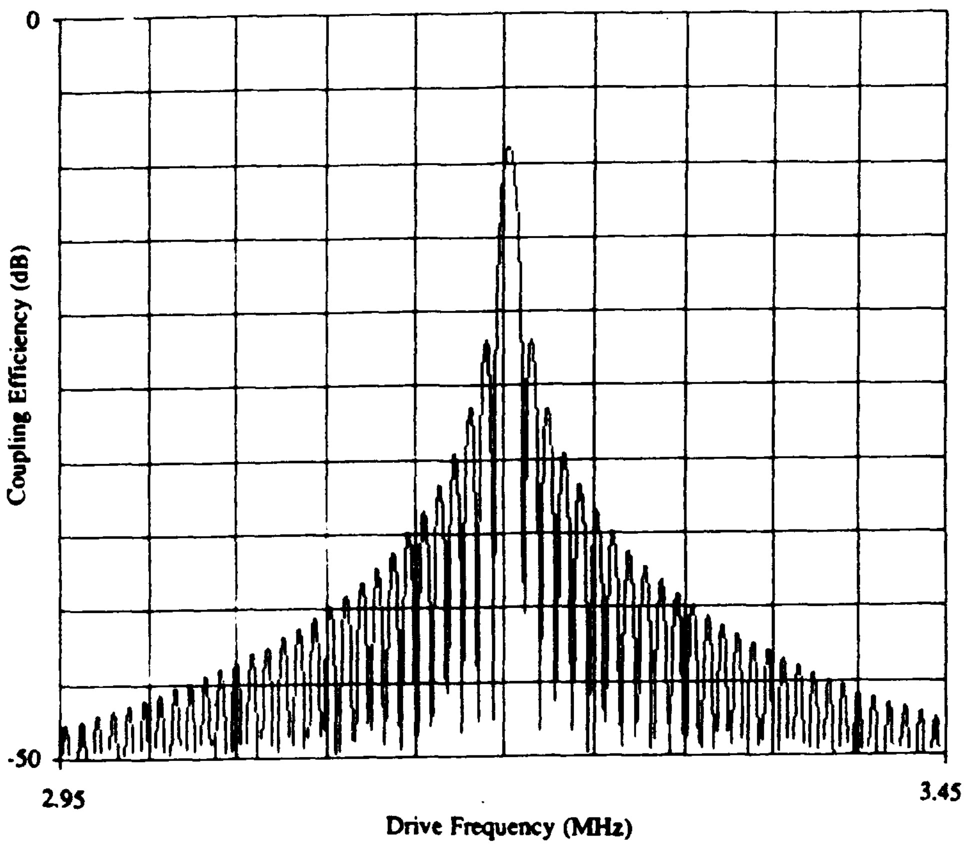


Figure 3.6 : Theoretical coupling efficiency versus drive frequency

4. Further experimentation and proposals

4.1 Other torsional-birefringent devices

Since completion of testing of the torsional-birefringent fibre frequency shifter reported in section 3, several other devices have been constructed. However, testing of these devices has been hampered by mechanical failures and thus no improvements in performance can be reported.

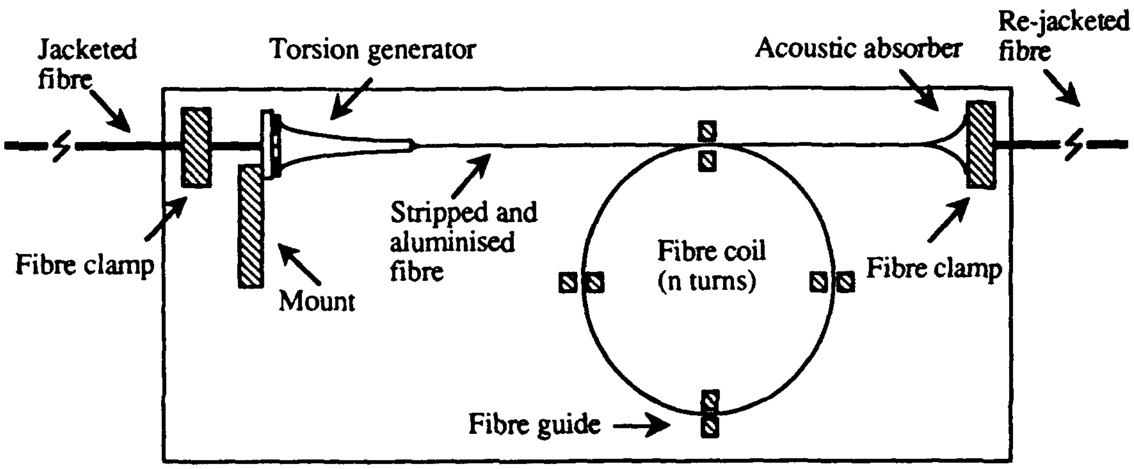
There are two features of the design which can be relatively simply changed in order to seek increased optical coupling efficiency. Firstly, the number of PZT elements from which the torsional transducer is constructed may be changed. It is thought that, with four PZT elements, there was the possibility that the two orthogonally positioned pairs may be generating two separate torsional waves rather than contributing to a single acoustic wave. The two waves may thus be coupling together within the horn in such a manner as to adversely affect the overall performance of the device. Hence, a torsional-birefringent fibre shifter was constructed which incorporates only one pair of PZT elements as the torsional transducer. Unfortunately, no coupling was observed with this device, though this may not be solely due to the change in configuration as the horn tip-fibre joint was imperfect.

The second change is to increase the interaction length of the fibre shifter. Several devices have been constructed with an interaction length of >1m. This evidently requires the use of concomitantly longer lengths of optical fibre stripped of its plastic buffer jacket and leads to a considerably more fragile structure. This has lead to several fibre breakages. To try to prevent such breakages, in later devices the stripped fibre was aluminised. Aluminisation improves the shear strength of the fibre and permits it to be bent with a radius of curvature as small as 5mm without breaking. However, simple shear failure within the main fibre body is not the principal problem (although apparently spontaneous fracture can occur as stripped fibre ages and absorbs atmospheric water into microcracks - this should be improved by hermetically sealing the fibre with the metal coating). The point where most breakages occur is at the horn tip-optical fibre joint. This problem has two sources, the brittleness introduced by sealing the joint using a flame and the subsequent weight of the fibre suspended from that joint. The former problem would be cured by electrical arc fusion of the joint and the latter indicates that, until the joint is consistently stronger, the interaction length should not be increased beyond the previous ~0.5m.

4.2 Proposals

An additional disadvantage of increasing the interaction length is that the overall length of the device becomes impractical. However, one may be able to take advantage of the ability to bend the aluminised fibre to produce a large interaction length but compact structure by forming a coil with the fibre as shown in figure 5.1. This concept is suggested by the coiled-wire torsional ultrasonic delay lines shown in reference 12. The effect of the additional bend-induced linear birefringence can be calculated[13] and made negligible for bend radii larger than a few cms.

Finally, the possibility of using elliptical core high birefringent fibre rather than the bow-tie fibre used in our experiments could be investigated. The former type of fibre exhibits 'shape' linear birefringence whereas the latter exhibits 'stress' linear birefringence. The birefringence of the latter type is considerably more temperature dependent[13]. This is undesirable as the beatlength of the fibre will also vary with temperature leading to poorer matching of the longitudinal phase matching condition and concommittant reduction in the coupling efficiency.



Compact ruggedised torsional birefringent fibre frequency shifter

Figure 5.1 : Schematic of compact, coiled, torsional-birefringent fibre frequency shifter.

Acknowledgement

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